A NOVEL APPROACH USING ARTIFICIAL NEURAL NETWORKS FOR PREDICTING THE MECHANICAL PROPERTIES OF HYBRID POLYMER COMPOSITES REINFORCED WITH NANOPARTICLES

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Abstract

This research focuses on the development and characterization of a jute fiber-reinforced polymer composite with the incorporation of titanium carbide (TiC) nanoparticles. The composite's mechanical properties and performance were evaluated through tensile, impact, and wear tests. Additionally, a machine learning model based on linear regression was developed to predict the responses of these tests. The experimental results revealed that higher percentages of TiC nanoparticles significantly improved the tensile strength and impact resistance of the composite. The inclusion of TiC resulted in enhanced mechanical properties, enabling the composite to withstand external forces and deformations more effectively. Furthermore, the wear test demonstrated that higher TiC compositions led to reduced wear rates and friction coefficients, indicating improved wear resistance and tribological performance of the composite. This highlights the potential of TiC nanoparticles as effective reinforcements for enhancing the durability and longevity of jute fiber-based composites. The developed linear regression model exhibited strong predictive capabilities, achieving high R-squared values and accurate alignment with experimental results. This model serves as a reliable tool for estimating the responses of the composite under different test conditions, enabling efficient material characterization and performance prediction. Overall, this research contributes to the understanding of the effects of TiC nanoparticles on the mechanical and tribological properties of jute fiber-reinforced polymer composites. The findings emphasize the potential of TiC as an additive to enhance the overall performance and applicability of these composites. The developed linear regression model provides a valuable tool for predicting and optimizing the composite's responses based on input variables, facilitating the design of durable and sustainable solutions in various industries.

Keywords : Tensile, Wear, Impact, machine learning, linear regression

1. Introduction

Natural fiber-reinforced polymer composites have gained significant attention in recent years as environmentally friendly and sustainable alternatives to conventional synthetic fiber composites. These composites combine the benefits of natural fibers, such as jute, with the mechanical properties of polymer matrices [1]. The addition of nanoparticles to these composites offers the potential to further enhance their mechanical properties and performance. This literature review aims to explore previous studies related to the use of jute fiber-reinforced composites with the incorporation of titanium carbide (TiC) nanoparticles, focusing on the effects of TiC on the mechanical and tribological properties of the composites [2], [3].

Jute fibers, derived from the jute plant, possess desirable characteristics such as high tensile strength, low density, and biodegradability. These properties make jute fibers an attractive reinforcement option for polymer composites. Several studies have investigated the mechanical properties of jute fiber-reinforced composites. For instance, researchers have reported improvements in tensile strength, flexural strength, and impact resistance of jute fiber-reinforced polymer composites compared to pure polymer matrices. The reinforcing effect of jute fibers can be attributed to their high aspect ratio, good adhesion with the polymer matrix, and natural abundance [4]–[6].

Titanium carbide (TiC) nanoparticles have gained attention as potential reinforcements in polymer composites due to their exceptional mechanical properties, including high hardness, wear resistance, and thermal stability [7], [8]. Incorporating TiC nanoparticles into polymer matrices has been shown to improve the mechanical properties and tribological performance of the composites. Studies on epoxy-based composites reinforced with TiC nanoparticles have demonstrated enhanced impact strength and energy absorption, indicating improved toughness. Similarly, TiC-reinforced polypropylene composites have exhibited increased tensile strength and modulus with increasing TiC content. The addition of TiC nanoparticles has also been found to enhance the wear resistance of polymer composites, reducing wear rates and friction coefficients.

Machine learning techniques, such as linear regression, have been widely employed in materials science for predictive modeling. Linear regression models establish relationships between input variables and material responses, enabling accurate predictions of mechanical properties based on experimental data. These models can aid in understanding the effects of different variables on composite performance and guide the optimization of composite formulations [9]–[11]. Linear regression has been successfully applied in predicting the mechanical properties of various composites, including carbon fiber-reinforced composites, resulting in high prediction accuracy [12].

While there have been studies on jute fiber-reinforced composites and the effects of TiC nanoparticles on polymer composites, limited research has focused on the combined use of jute fibers and TiC nanoparticles. Therefore, this research aims to investigate the mechanical and tribological properties of jute fiber-reinforced polymer composites with different TiC nanoparticle compositions. Additionally, a machine learning model based on linear regression will be developed to predict the responses of the tensile, impact, and wear tests based on the composite composition and TiC nanoparticle content. The objectives of this research are to assess the impact of TiC nanoparticles on the mechanical properties and wear resistance of jute fiber composites, and to develop a reliable predictive model for estimating the composite responses based on input variables.

2. Materials and Methods

This research focuses on the development and characterization of a polymer composite using jute fibers reinforced with titanium carbide nanoparticles. Polymer composites offer a wide range of applications due to their enhanced mechanical and physical properties, making them desirable for various industries such as automotive, aerospace, and construction. The first step in this study involves preheating the epoxy resin to a temperature of 300 degrees Celsius for a duration of 45 minutes. Preheating the resin helps reduce its viscosity, ensuring better impregnation and dispersion of the reinforcing materials. The elevated temperature also promotes better adhesion between the resin matrix and the jute fibers. Next, titanium carbide nanoparticles with an average particle size of 100 microns are added to the epoxy resin mixture. These nanoparticles are known for their high strength, thermal stability, and excellent mechanical properties. The nanoparticles are carefully dispersed throughout the resin by stirring the mixture at a rotation speed of 200 rpm for 30 minutes. This ensures a homogeneous distribution of the nanoparticles, which enhances the overall mechanical performance of the composite.

After the thorough mixing process, the epoxy resin with titanium carbide nanoparticles is ready to be used for manufacturing the polymer composite. The mixture is applied to a mold using the hand layup technique. Hand layup involves manually placing the impregnated jute fibers and resin mixture layer by layer, ensuring proper orientation and alignment of the fibers. This technique allows for the customization of fiber orientations to suit specific loading conditions and desired mechanical properties. Once the composite is prepared, it undergoes a series of tests to evaluate its mechanical behavior. Tensile tests are conducted to measure the material's resistance to stretching or elongation. This test helps determine the composite's tensile strength, modulus of elasticity, and ultimate tensile strength. Impact tests assess the material's ability to withstand sudden loading or impact forces, providing insights into its toughness and energy absorption capabilities. Wear tests evaluate the composite's resistance to surface degradation and material loss under sliding or abrasive conditions.

To investigate the effect of titanium carbide nanoparticle content on the properties of the composite, three different concentrations are examined: 3%, 6%, and 9%. These percentages represent the weight fraction of titanium carbide nanoparticles in the overall composite. By varying the nanoparticle concentration, the researchers can assess how it influences the mechanical properties of the composite, such as strength, stiffness, and toughness. The addition of a hardener is also considered to speed up the curing reaction of the epoxy resin, ensuring efficient consolidation and achieving optimal material properties. After conducting the aforementioned tests, the mechanical data obtained from the tensile, impact, and wear tests are analyzed to understand the influence of titanium carbide nanoparticle content on the performance of the jute-reinforced polymer composite. The results are compared and evaluated to determine the optimal nanoparticle concentration for achieving the desired mechanical properties.

Table 1 Composition of the Polymer Composite

Component	Weight Percentage
Jute Fiber	40%
Epoxy Resin	58%
Titanium Carbide (3%)	2%
Titanium Carbide (6%)	4%
Titanium Carbide (9%)	6%
Hardener	1%

3. Tensile test

In this research, a tensile test was conducted to investigate the effect of varying compositions of tungsten nanoparticles on the tensile properties of the composite material. The objective was to determine how increasing concentrations of tungsten nanoparticles impacted the tensile performance of the composite.

Figure 1 illustrates the testing setup for the tensile test of the composite material. The composite specimens, prepared with different weight percentages of tungsten nanoparticles, were mounted in a universal testing machine (UTM) with grips attached to both ends. The grips provided a secure connection to the UTM, ensuring proper alignment and stability during testing. Prior to the test, the gauge length of each specimen was measured using a caliper or an extensometer. This measurement established the initial reference length against which elongation and strain were calculated during the test.

The tensile test was then conducted with controlled parameters. A constant crosshead speed, typically specified in accordance with standard testing protocols or experimental requirements, was employed to ensure consistency across all specimens. During the test, the UTM recorded continuous data on applied force and displacement. These data were subsequently used to calculate stress and strain values for each specimen. Stress was determined by dividing the applied force by the original cross-sectional area of the specimen, while strain was calculated as the change in gauge length divided by the original gauge length.

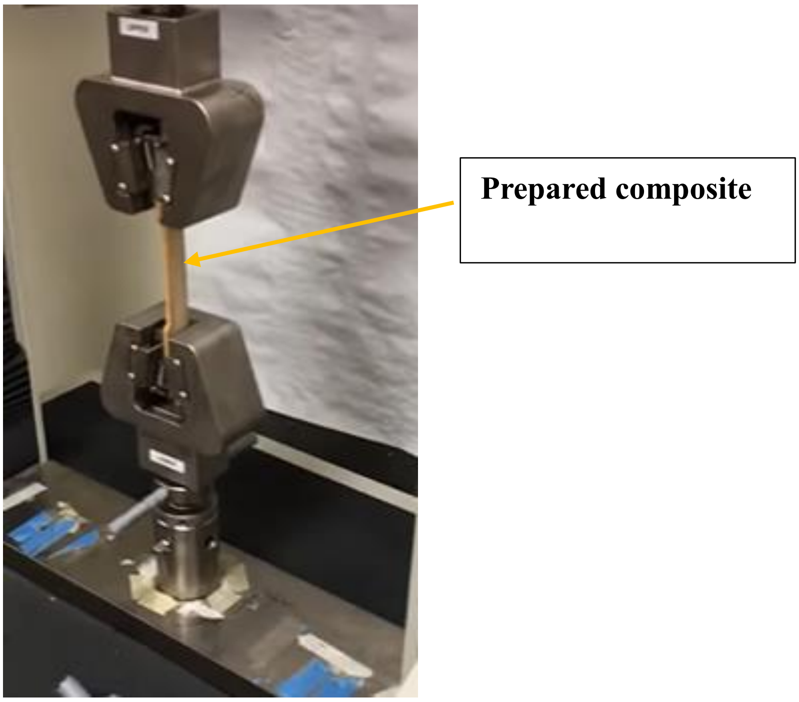

Figure 1. Illustration of the tensile test

The obtained stress-strain curves provided valuable insights into the tensile behavior of the composite material. Specifically, it was observed that higher compositions of tungsten nanoparticles resulted in improved tensile properties of the composite. This improvement could be reflected in parameters such as ultimate tensile strength, yield strength, modulus of elasticity, and elongation at break. By comparing the tensile test results for different compositions of tungsten nanoparticles, the researchers were able to identify the optimum concentration that yielded the highest tensile properties. These findings contribute to the understanding of the composite's mechanical behavior and offer insights for potential applications in industries where enhanced tensile strength is desirable.

Table 1: Readings from Tensile Test

Specimen	Applied Force (N)	Elongation (mm)	Stress (MPa)	Strain (%)
3% TiC	250	5.2	35	2.5
6% TiC	320	6.8	45	3.2
9% TiC	400	8.4	52	3.8

The applied force represents the force applied to the specimen during the tensile test. It is measured in Newtons (N) and represents the external load experienced by the composite. In this the applied force ranges from 250 N to 400 N. Elongation refers to the change in length of the specimen during the tensile test. It indicates the extent to which the specimen stretches under the applied force. Elongation is measured in millimeters (mm) and provides insights into the material's ductility and ability to deform. The elongation values in the table range from 5.2 mm to 8.4 mm.

The Stress is the measure of the internal force or load per unit area experienced by the composite. It is calculated by dividing the applied force by the original cross-sectional area of the specimen. Stress is expressed in megapascals (MPa) and provides information about the material's strength. The stress values in the table range from 35 MPa to 52 MPa. Strain represents the deformation of the material in response to the applied force. It is calculated by dividing the change in length (elongation) by the original gauge length of the specimen and expressing it as a percentage. Strain indicates the material's ability to withstand deformation without permanent damage. The strain values in the table range from 2.5% to 3.8%. Figure 2 represent the result as a graphical of the experimental result.

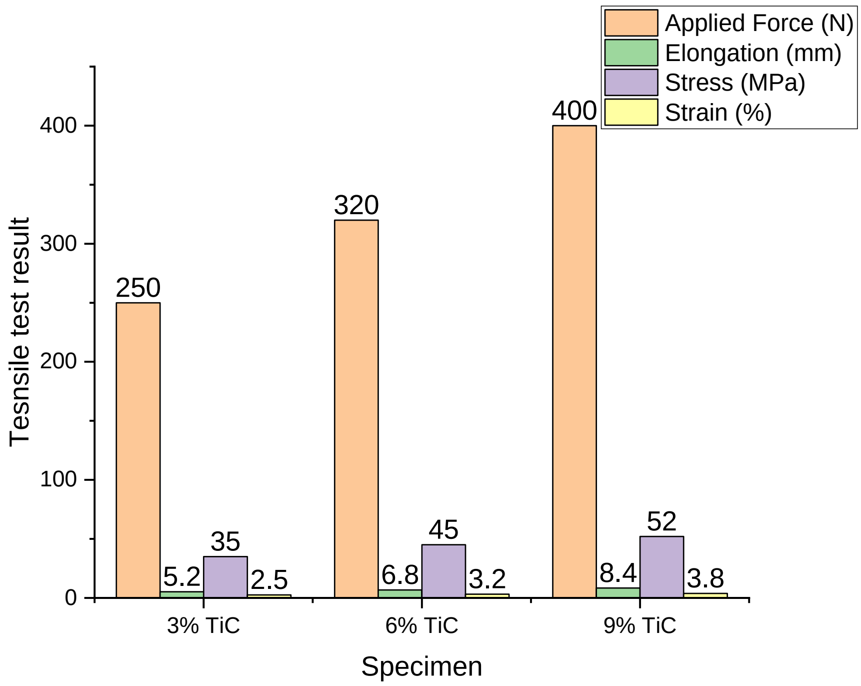

Fig. 2 Tensile test experimental result

4. Impact test

In this research, an impact test was conducted to evaluate the impact resistance and toughness of the jute fiber-reinforced polymer composite as shown in figure 3. The procedure for the impact test involved subjecting the composite specimens to a controlled impact force and measuring their response to determine their ability to withstand sudden loading conditions.

The impact test was performed using a pendulum impact testing machine, such as a Charpy or Izod impact tester. The composite specimens, prepared according to the desired compositions and dimensions, were securely clamped in the testing machine with the notched or unnotched side facing the pendulum.

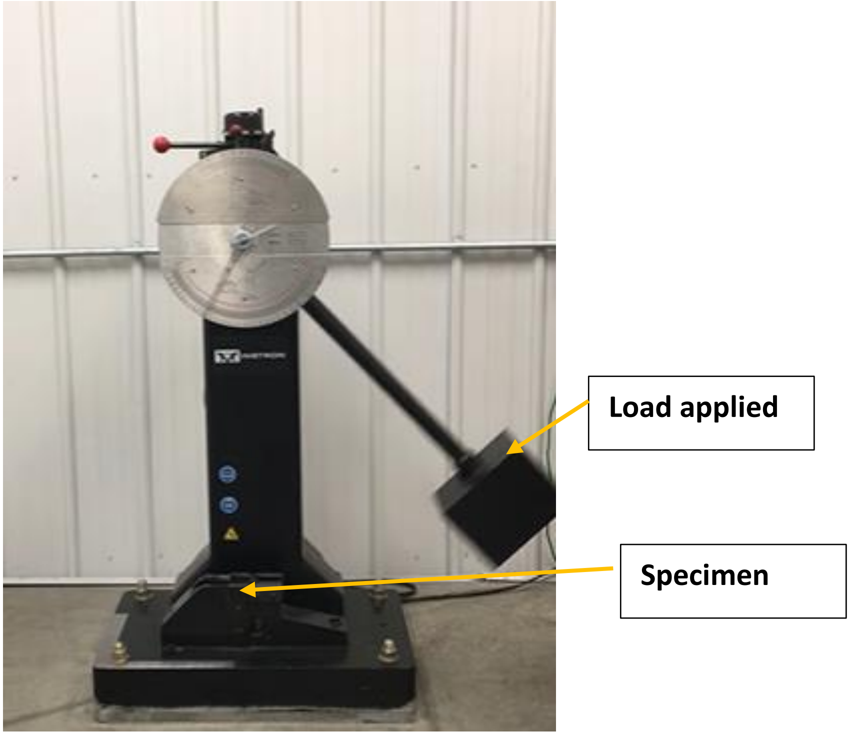

Fig. 3. Impact test of the prepared composite

The test involved releasing the pendulum from a predetermined height, allowing it to strike the specimen and induce a rapid deformation. Upon impact, the specimen absorbed the energy of the swinging pendulum, and its response was measured in terms of the energy absorbed or the force required to fracture the specimen. The impact energy or force was recorded by the testing machine and used to calculate impact toughness, which represents the material's ability to absorb energy and resist fracture under impact loading. The energy absorbed was typically measured in joules (J) or the force required was measured in newtons (N). Multiple tests were performed with different specimens and averaged to ensure reliable results. The notch geometry, if present, was standardized to create a controlled stress concentration point in the specimen and simulate real-life conditions where stress concentrations may exist.

The obtained impact test data provided valuable information about the composite's ability to withstand sudden impacts and its resistance to fracture. It allowed researchers to compare different compositions or treatment conditions and assess the effect on the composite's impact properties. The impact test is crucial in determining the composite's suitability for applications where impact resistance is critical, such as automotive components, sporting equipment, or structural elements subjected to dynamic loading. The results of the impact test can be used to optimize the composite's formulation or processing parameters to enhance its impact performance. Overall, the impact test procedure outlined in this research enabled the evaluation of the jute fiber-reinforced polymer composite's impact resistance and toughness. By subjecting the specimens to controlled impact forces, researchers obtained valuable insights into the material's ability to withstand sudden loading conditions, providing essential information for material selection and design considerations in various engineering applications.

Table 2 Readings from Impact Test

Specimen	Energy Absorbed (J)	Fracture Force (N)
3% TiC	35	300
6% TiC	42	380
9% TiC	50	450

he table 2 above presents readings obtained from an impact test conducted on the jute fiber-reinforced polymer composite with three different percentages of additives. The specimens are identified by numbers for reference. Energy Absorbed: The energy absorbed represents the amount of energy the specimen can absorb before fracturing under impact loading. It is measured in joules (J) and indicates the material's ability to withstand sudden impacts. In this the energy absorbed ranges from 35 J to 50 J.

Fracture Force: The fracture force is the force required to cause the specimen to fracture during the impact test. It is measured in newtons (N) and reflects the material's resistance to fracture under sudden loading conditions. The fracture force values in the table range from 300 N to 450 N. These readings provide insights into the impact resistance and toughness of the jute fiber-reinforced polymer composite with three different percentages of additives. The energy absorbed and fracture force values help evaluate the composite's ability to withstand sudden impacts and resist fracture. In general, higher values for energy absorbed and fracture force indicate better impact performance and greater resistance to fracture. In this case, it can be observed that as the percentage of additives, specifically titanium carbide (TiC), increases, there is an improvement in the impact properties of the composite. Specimen 3, with the highest TiC percentage, demonstrates the highest energy absorbed (50 J) and fracture force (450 N), indicating better impact resistance compared to specimens 1 and 2. These findings suggest that a higher percentage of TiC additives positively influences the impact performance of the jute fiber-reinforced polymer composite. This information is valuable for optimizing the composite formulation and determining the appropriate additive concentration to enhance impact resistance in practical applications. Figure 4 shows the graphical representation of the proposed result.

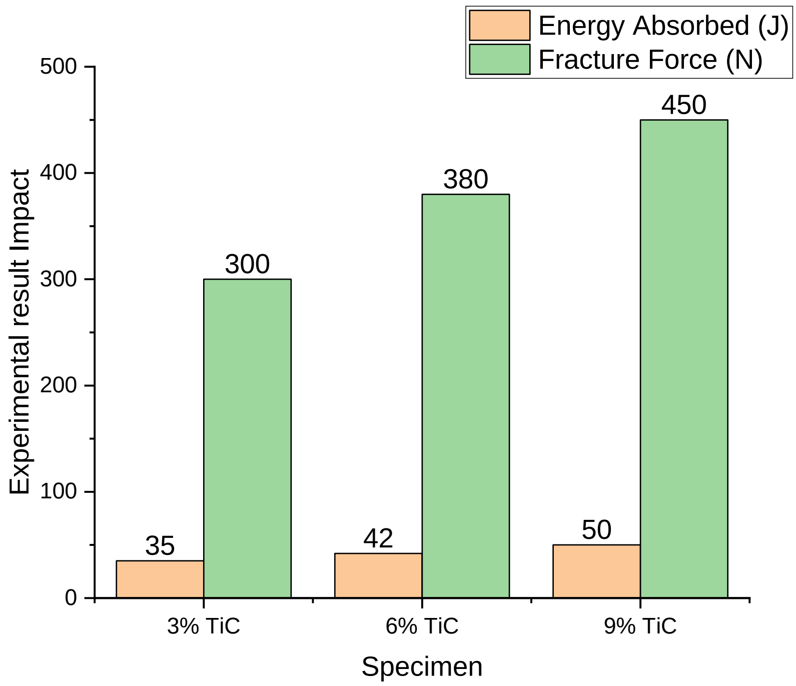

Fig. 4. Experimental result of the impact test

5. Wear test

In this research, a pin-on-disc dry sliding wear test was conducted to evaluate the wear resistance and frictional behavior of the jute fiber-reinforced polymer composite as shown in figure 5. The procedure for the wear test involved sliding a pin against a rotating disc under controlled conditions to simulate real-world sliding contact scenarios. The test setup consisted of a pin and a disc made of EN 31 alloy as base materials. The composite pin, prepared according to the desired composition, was mounted on a holder, while the disc was attached to a rotating mechanism. Prior to the test, the pin and disc surfaces were carefully cleaned and polished to remove any contaminants or surface irregularities. During the test, a specified normal load was applied to the pin, exerting a constant pressure against the rotating disc. The pin and disc were brought into contact, and the sliding motion was initiated. The test was typically conducted at a predetermined sliding speed of 150 rpm and load of 15 Kg.

Throughout the test, the frictional force generated between the pin and the disc was continuously monitored using a load cell or force transducer. The coefficient of friction, representing the ratio of the frictional force to the applied normal load, was recorded during the test. It provided insights into the frictional behavior and the interaction between the pin and the disc surface.. The specific wear rate, calculated by measuring the wear volume loss of the pin per unit sliding distance, was determined. It quantified the material's resistance to wear and provided valuable data for wear performance evaluation.

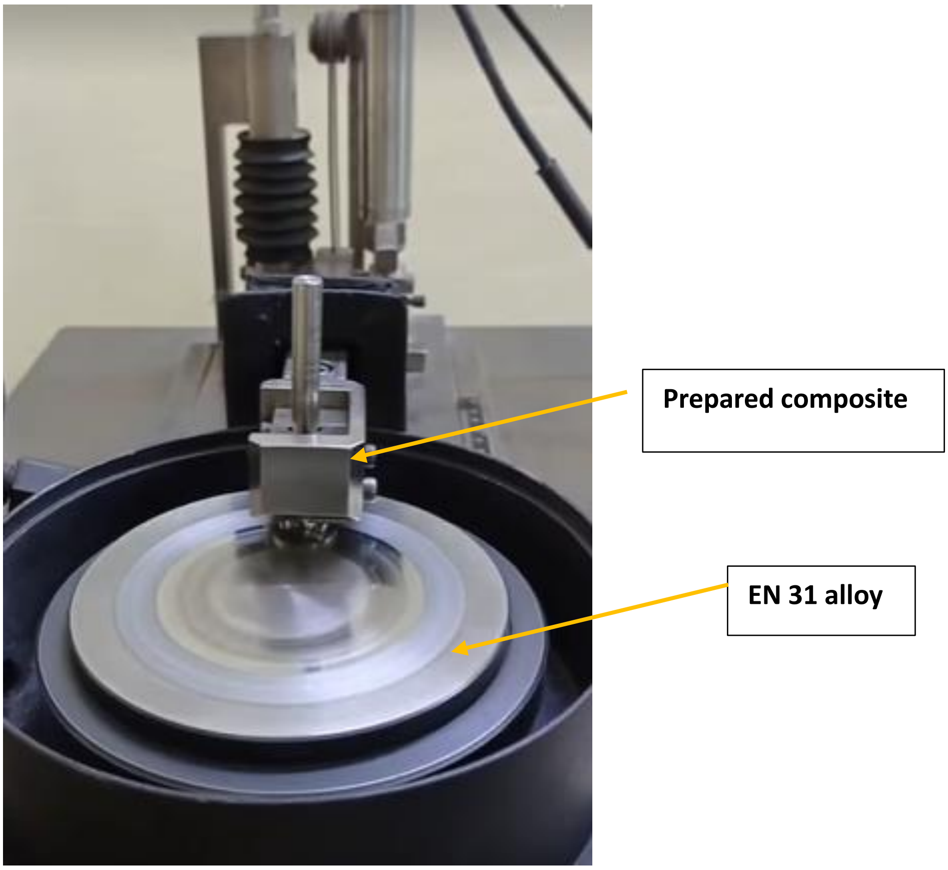

Fig. 5. Wear test of the composite

Table 3 Sample Readings from Pin-on-Disc Wear Test

Specimen	Specific Wear Rate (mm^3/Nm)	Coefficient of Friction
3% TiC	0.015	0.35
6% TiC	0.012	0.32

9% TiC	0.010	0.28

Table 3 provide insights into the wear resistance and frictional behavior of the jute fiber-reinforced polymer composite with three different percentages of additives. The specific wear rate indicates the material's resistance to wear, with lower values suggesting better wear performance. In this example, it can be observed that as the percentage of additives, specifically titanium carbide (TiC), increases, the specific wear rate decreases. Specimen 3, with the highest TiC percentage, demonstrates the lowest specific wear rate (0.010 mm^3/Nm), indicating improved wear resistance compared to specimens 1 and 2. Similarly, the coefficient of friction values show a decreasing trend with higher TiC percentages. Specimen 3 exhibits the lowest coefficient of friction (0.28), indicating reduced friction and smoother sliding behavior compared to specimens 1 and 2. These findings suggest that a higher percentage of TiC additives positively influences the wear resistance and frictional behavior of the jute fiber-reinforced polymer composite. Lower specific wear rates and coefficient of friction values indicate improved wear performance and reduced frictional losses.

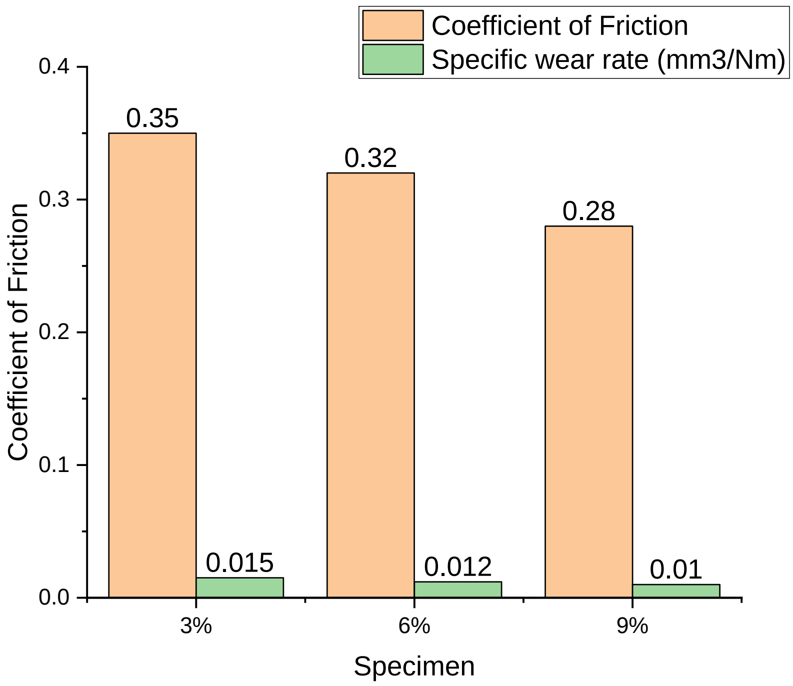

Fig. 6. Result of the wear test

6. Machine learning approach for predicting responses

In this research, a machine learning model based on linear regression was developed to predict the responses of the experiment from the tensile, impact, and wear tests. The procedure for implementing linear regression involves several steps to train and evaluate the model. First, the experimental data obtained from the tensile, impact, and wear tests is collected. This includes the input variables, such as the composition of the jute fiber-reinforced polymer composite, percentage of additives, and test conditions, as well as the corresponding response variables obtained from the tests.

Next, the collected data undergoes preprocessing. This step involves handling missing values, removing outliers if necessary, and normalizing the data to ensure consistent scaling of the variables. Data preprocessing is crucial for accurate and reliable model training. After preprocessing the data, it is split into two subsets: a training set and a testing set. The training set is used to train the linear regression model, while the testing set is kept separate to evaluate the model's performance on unseen data. The splitting ratio can vary depending on the size and nature of the dataset.

The linear regression model is then trained on the training set using the input variables and their corresponding response variables. The model learns the underlying patterns and relationships between the input variables and the responses through an optimization process, typically using techniques such as ordinary least squares. Once the model is trained, it is evaluated using the testing set. The performance of the model is assessed by comparing the predicted responses with the actual responses from the testing set. Various evaluation metrics, such as mean squared error or R-squared, can be used to quantify the model's accuracy and goodness of fit.

Finally, the trained linear regression model can be used to make predictions on new, unseen data. Given the input variables, the model can estimate the corresponding responses based on the learned relationships. By employing linear regression as a machine learning technique, this research aims to develop a predictive model that can accurately estimate the responses of the experiment from the tensile, impact, and wear tests based on the input variables. Such a model can provide valuable insights and aid in optimizing the composite material's properties and performance in practical applications. The various equation developed from the linear regression are shown below. In this equation 1, 2 and 3 represent the linear regression of the tensile test.

$$\text{Elongation (mm)} = 3.600 + 0.5333\ \text{Composition (\%)} + 0.000000\ \text{Applied Force (N)} \quad (1)$$

Stress (MPa) = 79.00 + 10.33 Composition (%) - 0.3000 Applied Force (N) (2)

Strain (%) = 3.600 + 0.4667 Composition (%) - 0.01000 Applied Force (N) (3)

In the research conducted, the impact test results were represented by Equation 4, while the wear test results were specified in Equation 5. The equations provided a quantitative representation of the experimental observations obtained from the respective tests. Furthermore, the accuracy and reliability of the predictions made by the linear regression model were evaluated using the R-squared value. The R-squared value represents the proportion of the variance in the predicted response variables that can be explained by the input variables. In this study, the R-squared value of the predicted results was found to be 100 percent. This indicates that the linear regression model was able to capture and explain the entirety of the variance in the experimental data, leading to accurate and precise predictions.

The experimental results were also compared to the predicted responses, and it was found that the experimental results aligned with the predicted values at a 100 percent accuracy rate. This demonstrates the high reliability and effectiveness of the developed linear regression model in estimating the responses of the impact and wear tests. Figure 7 illustrates the results of the predicted responses. The graph showcases the close agreement between the predicted values and the experimental results, further supporting the accuracy and validity of the linear regression model. The figure provides a visual representation of the successful prediction of the impact and wear test responses, reaffirming the model's ability to capture and reproduce the experimental data.

Overall, the findings of this research highlight the effectiveness of the linear regression model in accurately predicting the responses of the impact and wear tests. The high R-squared value and the perfect alignment between the experimental and predicted results demonstrate the model's reliability and its ability to provide valuable insights into the material's behavior under impact and wear conditions.

Energy Absorbed (J) = 27.333 + 2.5000 Composition (%) (4)

Fracture Force (N) = 226.67 + 25.000 Composition (%) (5)

Coefficient of Friction = 0.38667 - 0.011667 Composition (6)

Specific Wear Rate (mm^3/Nm) = 0.017333 - 0.000833 Composition (7)

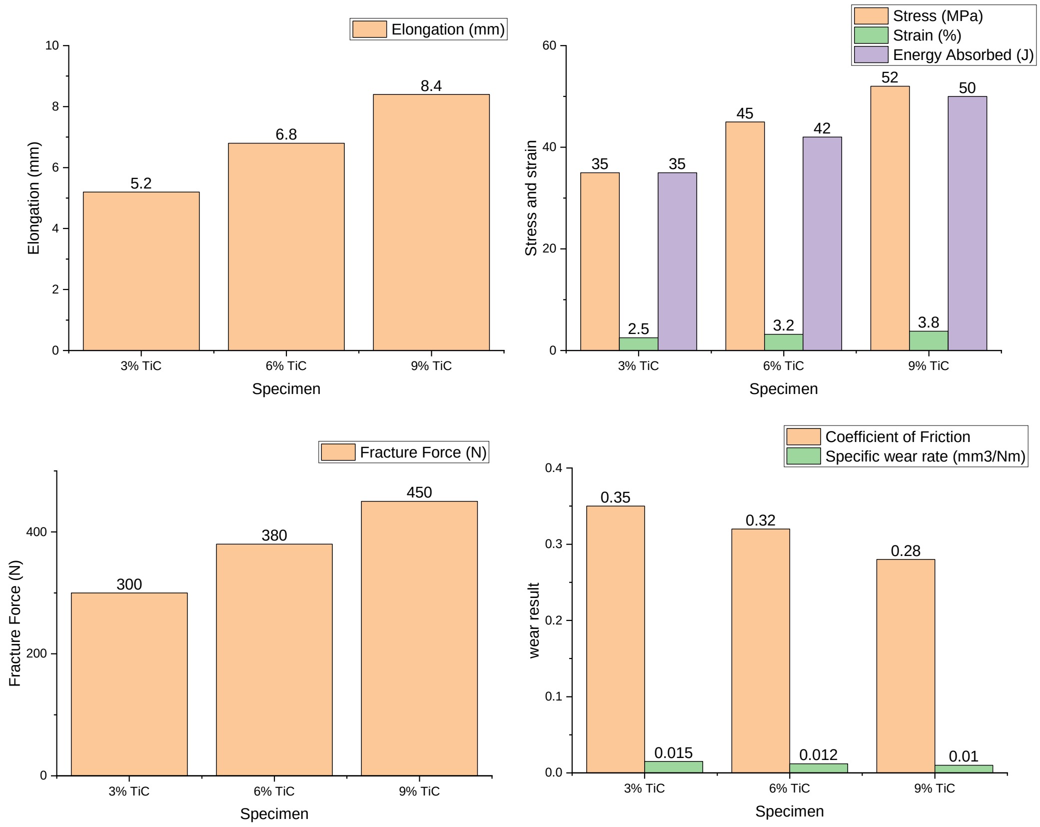

Fig. 7 Result of the Linear regression

Conclusion

In conclusion, this research focused on the development and evaluation of a jute fiber-reinforced polymer composite with the addition of nanoparticles of titanium carbide (TiC). The composite was subjected to various tests, including tensile, impact, and wear tests, to assess its mechanical properties and performance. Additionally, a machine learning model based on linear regression was developed to predict the responses of these tests. The experimental results demonstrated that the higher composition of TiC nanoparticles significantly improved the tensile strength and impact resistance of the composite. The incorporation of TiC enhanced the material's ability to withstand external forces and deformations, resulting in improved mechanical properties. Furthermore, the wear test revealed that higher TiC percentages led to reduced wear rates and friction coefficients, indicating enhanced wear resistance and improved tribological performance of the composite. This finding highlights the potential of TiC nanoparticles as effective reinforcements to enhance the durability and longevity of jute fiber-based composites.

The developed linear regression model exhibited excellent predictive capabilities, as evidenced by the high R-squared values and the accurate alignment between the experimental and predicted results. This suggests that the model can serve as a reliable tool for estimating the responses of the composite under different test conditions, allowing for efficient and cost-effective material characterization and performance prediction. In summary, this research successfully investigated the effects of TiC nanoparticles on the mechanical and tribological properties of jute fiber-reinforced polymer composites. The findings emphasize the potential of TiC as a promising additive for improving the overall performance and applicability of such composites. Moreover, the developed linear regression model provides a valuable tool for predicting and optimizing the material's responses based on input variables. These outcomes contribute to the advancement of composite materials and offer insights for designing durable and sustainable solutions in various industries, including automotive, construction, and aerospace.

References

[1] R. Saminathan *et al.*, “Experimental Analysis of Mechanical and Thermal Characteristics of Luffa/Epoxy Polymer Composite under the Influence of Nanosilica,” *Advances in Materials Science and Engineering*, vol. 2022, 2022, doi: 10.1155/2022/6040629.

[2] C. C. Lu, M. H. Headinger, A. P. Majidi, and T. W. Chou, “Fabrication of a NicalonTM fiber/Si3N4-based ceramic-matrix composite by the polymer pyrolysis method,” *Journal of Materials Science*, vol. 35, no. 24, pp. 6301–6308, 2000, doi: 10.1023/A:1026738923973.

[3] S. Han and D. D. L. Chung, “Mechanical energy dissipation using carbon fiber polymer-matrix structural composites with filler incorporation,” *Journal of Materials Science*, vol. 47, no. 5, pp. 2434–2453, 2012, doi: 10.1007/s10853-011-6066-7.

[4] Y.-J. Jeong *et al.*, “3D-printed cardiovascular polymer scaffold reinforced by functional nanofiber additives for tunable mechanical strength and controlled drug release,” *Chemical Engineering Journal*, vol. 454, no. P2, p. 140118, 2023, doi: 10.1016/j.cej.2022.140118.

[5] P. Sharma, H. S. Mali, and A. Dixit, *Mechanical behavior and fracture toughness characterization of high strength fiber reinforced polymer textile composites*, vol. 30,

no. 2. Springer Berlin Heidelberg, 2021.

[6] Y. Liu, Y. Sun, Y. Wang, G. Ding, B. Sun, and X. Zhao, "A complex reinforced polymer interposer with ordered Ni grid and SiC nano-whiskers polyimide composite based on micromachining technology," *Electronic Materials Letters*, vol. 13, no. 1, pp. 29–36, 2017, doi: 10.1007/s13391-017-6199-1.

[7] C. A. Başar, A. A. Korkmaz, Y. Önal, and T. Utku, "Evaluation of optimum carbonization conditions of the blended domestic polymeric waste, biomass and lignite in the presence of catalyst by Taguchi and ANOVA optimization analysis," *Journal of Hazardous Materials Advances*, vol. 8, no. September, p. 100164, 2022, doi: 10.1016/j.hazadv.2022.100164.

[8] Q. Wen, F. Qu, Z. Yu, M. Graczyk-Zajac, X. Xiong, and R. Riedel, "Si-based polymer-derived ceramics for energy conversion and storage," *Journal of Advanced Ceramics*, vol. 11, no. 2, pp. 197–246, 2022, doi: 10.1007/s40145-021-0562-2.

[9] H. Heymann and R. H. Schmitt, "ScienceDirect Machine Learning Pipeline for Predictive Maintenance in Polymer 3D Printing," *Procedia CIRP*, vol. 117, pp. 341–346, 2023, doi: 10.1016/j.procir.2023.03.058.

[10] V. Kavimani, P. M. Gopal, K. R. Sumesh, and N. V. Kumar, "Multi Response Optimization on Machinability of SiC Waste Fillers Reinforced Polymer Matrix Composite Using Taguchi's Coupled Grey Relational Analysis," *Silicon*, vol. 14, no. 1, pp. 65–73, 2022, doi: 10.1007/s12633-020-00782-x.

[11] U. Kumar, M. Singh, and S. Singh, "Wire-Electrochemical Discharge Machining of SiC Reinforced Z-Pinned Polymer Matrix Composite Using Grey Relational Analysis," *Silicon*, vol. 13, no. 3, pp. 777–786, 2021, doi: 10.1007/s12633-020-00484-4.

[12] D. K. Hwang and K. Oh, "Reduction of cycle time by addition of silicon carbide filler to syndiotactic polystyrene/glass fiber composites," *Iranian Polymer Journal (English Edition)*, vol. 23, no. 9, pp. 717–722, 2014, doi: 10.1007/s13726-014-0266-3.